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APPLICATION FOR

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Be it known that we, Sergey S. Sarkisov, a citizen of the Ukraine, residing at 2305 Fleer Circle, Huntsville, AL 35803; Michael J. Curley, a citizen of the United States, residing at 4110 Triana Blvd., Huntsville, Al 35805; Grigory Adamovsky, a citizen of the United States, residing at 5102 Lansdowne Dr., Solon, Oh 44139; Sergey S. Sarkisov, Jr., a citizen of the United States, residing at 2305 Fleer Circle, Huntsville, AL 35803; Aisha B. Fields, a citizen of the United States, residing at 2205 Norris Rd., Huntsville, AL 35810; have invented a new and useful "Bimorphic Polymeric Photomechanical Actuator".

BACKGROUND OF THE INVENTION

The present invention relates generally to the conversion of the photonic energy of light into mechanical work in the form of dynamic motion of a mechanical structure. More particularly, this invention pertains to an apparatus and methods for generating rectilinear, curvilinear, or rotational movement of a mechanical structure by controlling the illumination of a light directed upon a new type of photosensitive body having photomechanical characteristics. Even more particularly, this invention

pertains to a bimorphic polymeric photomechanical apparatus and method for converting light into movement.

Progress in the development of optic fiber technology and compact laser light sources has brought to life a great variety of optical sensors for almost every trade. Fiber optic based sensors have been incorporated into “smart” materials and structures, such as "smart skins", etc. Polymeric "smart skin" materials provide the useful structural properties characteristic of polymers while permitting exploitation of the electronic and photonic properties of miniaturized optical sensor systems. However, these systems lack simple and compact actuators that can be driven by the same low power light radiation used to operate the optical sensor systems. Current solutions employ electrically-driven actuators, which require voltage and current to be delivered by wires from an electric power source. The optical signal still must be converted into an electric current that can control the electrically-driven actuator. The fast growing industry of optical switching also experiences a similar problem. Currently available optical switches typically employ either electrically-driven piezoelectric actuator elements requiring external high voltage for actuation or converse piezoelectric driven actuator elements requiring a high power density light to cause actuation. These optical switches need either a relatively high power light source or external high voltage source to be applied to a switch.

The prior art is illustrated in the photo-driven actuator previously described by Uchino in "Recent topics of ceramic actuators. How to develop new ceramic devices",

Ferroelectrics, Vol. 91,281-292 (1989). This prior art actuator is based on the photostrictive effect exhibited by piezoelectric lead lanthanum zirconate titanate (PLZT) ceramics in the presence of ultraviolet light. Shining ultraviolet light on a single PLZT body will not make the material move greatly. Instead, a complex arrangement of paired wafers is needed to magnify the displacement. Two very thin layers of PLZT are bonded together with opposing polarization directions and conducting material connecting the edges. Light shone on one wafer creates expansion and an electric field that goes through the conducting material and is applied on the second layer. The voltage triggers the piezoelectric effect in the second layer, which contracts, bending the entire double wafer. Unfortunately, when the illumination is shut off, it can take several minutes for the material to return to its original shape, so, in order to have any kind of quick response system, the second wafer must be illuminated to cause the shape change in the other direction.

The disadvantages of this and the other prior art are significant when designing a useful, low power photo-driven actuator or photo-driven fast acting switch. The body of the photosensitive material is made of solid piezoelectric PLZT ceramics and is hard to shape and mold. The PLZT actuator must be driven only by UV radiation, such as 380 nm and shorter wavelength, produced by high power high pressure arc lamps or UV lasers. UV radiation has significant attenuation losses

when delivered through conventional optic fibers. The response of the PLZT actuator is very slow (several seconds). The maximum mechanical displacement generated by PLZT ceramics in response to illumination by light is short since the ceramic is hard, brittle, and has low strain before it fractures. As a result of these factors, PLZT ceramics' conversion efficiency of light energy into mechanical work is low.

Thus, there is a great need for a simple, efficient, and compact actuator, which can be driven by low power light radiation in the visible or mid-infrared range delivered through conventional optic fibers. The actuator should be suitable for integration with optical sensors and optical actuators of the same or different type. What is needed, then, is a photomechanical actuator as described herein.

SUMMARY OF THE INVENTION

The present invention is directed towards bimorphic polymeric photomechanical apparatus and methods for converting light into movement. Embodiments of the invention and advantages are shown for causing movement of a bimorphic polymeric photomechanical body by illuminating the body with a light beam to produce a photomechanical deformation of the body. Embodiments of the invention and advantages are shown for using a pulsed light output on a reciprocating bimorphic polymeric photomechanical body to create repetitive movements. This reciprocating body is shown in one preferred embodiment as a polyvinylidene fluoride

(PVDF). Further embodiments and advantages provide improved control by using multiple light sources to provide multiple ranges of movement, including using multiple bimorphic polymeric photomechanical bodies to provide different ranges of movement and including creating these multiple ranges of movement with a single bimorphic polymeric photomechanical body.

A further apparatus and method with particular utility is provided in a low power optically controlled optical switch that allows both the control signal and the transferred through signal to be an optical signal.

Methods of the present invention include a method of generating repetitive movement in bimorphic polymeric photomechanical bodies with light, a method for controlling movements in bimorphic polymeric photomechanical bodies by controlling the light illumination frequency and pattern, and a method for controlling movements in bimorphic polymeric photomechanical bodies with light by illuminating multiple areas of a single bimorphic polymeric photomechanical bodies or by illuminating multiple bimorphic polymeric photomechanical bodies areas.

Other objects and further scope of the applicability of the present invention will become apparent from the detailed description to follow, taken in conjunction with the accompanying drawing, wherein like parts are designated by like reference numerals.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a schematic representation of a bimorphic polymeric photomechanical body.

Fig. 2 is a schematic representation of the bimorphic polymeric photomechanical body of Fig. 1 using a light output to create bimorphic movement.

Fig. 3 is a schematic representation of a bimorphic polymeric photomechanical body using a pulsed light output to create movement of a reciprocating bimorphic polymeric photomechanical actuator.

Fig. 4 is a schematic representation of a two body, multiple movement bimorphic polymeric photomechanical actuator.

Fig. 5 is a schematic representation of a three body, multiple movement bimorphic polymeric photomechanical actuator.

Fig. 6 is a schematic representation of a single body multiple movement bimorphic polymeric photomechanical actuator.

Figs. 7a and 7b are schematic representations of bimorphic polymeric photomechanical actuators in optically driven electronic switches.

Fig. 8 is a schematic representation of a bimorphic polymeric photomechanical actuator in a fluidic diaphragm pump.

Fig. 9 is a schematic representation of a bimorphic polymeric photomechanical actuator in a cantilevered beam-resonance chamber fluidic pump.

Figs. 10a and 10b are schematic representations of bimorphic polymeric photomechanical actuator in a self-acting light beam focusing/defocusing apparatus.

Figs. 11a and 11d are schematic representations of bimorphic polymeric photomechanical actuators in photonic switches.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

The present invention is directed to an apparatus and method that converts light into mechanical work by illuminating a photosensitive portion of a flexible photomechanical body to produce mechanical deformation of the body. A photomechanical body comprises a photomechanical material, which is herein defined as a photosensitive material that exhibits a photomechanical effect when illuminated. A photomechanical effect is herein defined as a bulk dimensional change in a photosensitive body induced by the influence of an applied field of light energy, such as a beam of light. Various embodiments of the present invention utilize this mechanical deformation of a photomechanical body to convert light energy into mechanical work. A description of a prototypical embodiment of the present invention illustrates the several mechanisms by which light interacts with photosensitive materials to produce a photomechanical effect within a photosensitive material.

Figure 1 shows one embodiment of the apparatus 10 of the present invention. A photomechanical body 20 comprising a photomechanical polymeric material 30 is shown affixed to a base 75. The photomechanical body 20 has a normal state surface 21 defining its normal bulk dimensions without an applied field of light illuminating the photomechanical body 20. A light source 40 is shown generating a light output 50. In this embodiment, the light output 50 is adapted to emit light in the visible or infra-red light spectrum. The emissions can be discrete frequencies emissions, broadband emissions or continuous emissions. The emissions can be combined to produce numerous variations. Light output 50 is shaped as necessary to illuminate a desired portion of normal state surface 21. That portion of normal state surface 21 is termed the illumination surface 25. The illumination surface 25 comprises a photomechanical polymeric material 30. The photomechanical polymeric material 30 of the photomechanical body 20 is subjected to an applied field of selected light energy 51 by the illuminating light output 50 and undergoes a photomechanical effect that causes deformation of its normal state surface 21 and its normal bulk dimensions. Such change in bulk dimension is shown in Figure 2 by the actuated state surface 22 of the photomechanical body 20. Upon removal of the illuminating light output 50, the photomechanical body 20 rapidly returns to its original normal state surface 21 and its normal bulk dimensions. In the embodiment shown in Figure 2, the deformation is essentially elastic. Figure 2 further shows the path 95 swept out by the end of the photomechanical body 20

distal to the base 75 as the photomechanical body 20 deforms between its normal state surface 21 and its actuated state surface 22. One skilled in the art will recognize that the elastically deforming photomechanical body 20 can be used as an actuating mechanism for transforming light energy into another energy form by positioning a receiving structure so that the photomechanical body 20 contacts a movable receiving structure as the photomechanical body 20 undergoes deformation. One skilled in the art will recognize that the elastically deforming photomechanical body 20 can also be used as an actuating element for positioning a contact in switching mechanisms such as optical switches or electro-optical switches.

For the embodiment of the current invention shown in Figure 1, the dominant mechanism by which light produces a photomechanical effect is the photothermal mechanism. As stated above, the polymeric photomechanical material 30 comprises a polymeric photosensitive material 31. Light energy is absorbed by the polymeric photosensitive material 31 and converted to heat. The material's temperature increases, which, through thermal expansion of the bulk material, results in mechanical deformation. Typical characteristic time of the photothermal mechanism is of the order of milliseconds and the magnitude of the effect is large. Strain (relative bulk dimensional deformation) due to the photothermal mechanism can be 1.0% and higher. In one embodiment of the

invention, the required illumination intensity of the photothermal mechanism is of the order of .01 W/cm^2.

One secondary mechanism by which light produces a photomechanical effect in this embodiment of the present invention is photostriction. The photostriction mechanism is a combination of photoelectric and converse piezoelectric mechanisms. Light generates an electric field in the photoelectric material through photoconductance, photovoltaic, pyroelectric effects, or a combination thereof. The electric field produces mechanical deformation due to piezoelectricity. Typical characteristic time of the photostriction mechanism is greater or equal to few milliseconds and the magnitude of the effect of photostriction does not exceed 0.5% strain. In one embodiment of the invention, the required illumination intensity of the photostriction mechanism is of the order of $4x10^{-3}$ W/cm^2. However, the contribution of the photostriction mechanism to the photomechanical effect may be significantly limited by heating effects of the illuminating light.

An additional secondary mechanism by which light produces a photomechanical effect in this embodiment is electrostriction. Light generates an optical field gradient on the interface boundary between two dielectric media. This causes the deformation of the boundary and contributes to mechanical deformation of the photomechanical body 20. Typical characteristic time of the electrostriction mechanism is of the order of 10^{-9} seconds and the magnitude of the effect of electrostriction is of the order of 0.01% strain. In one embodiment of the invention,

the required illumination intensity of the electrostriction mechanism is of the order 10^3 W/cm^2.

A tertiary mechanism by which light produces a photomechanical effect in this embodiment is molecular reorientation. Molecular reorientation is a mechanism that, under the right conditions, contributes to the photomechanical effect. If the illuminating light is polarized and illuminates a photosensitive molecule, the long axis of the photosensitive molecule will align along the direction of the optic field. If these photosensitive molecules are embedded in a polymer, the molecule-polymer interaction will stress the polymer and result in deformation. The molecular reorientation mechanism can be fast (characteristic time of the order of 10^{-12} seconds) with little mechanical deformation (less than 0.001% strain) or it can be very slow (characteristic time of the order of 0.5 hour) with pronounced mechanical deformation (up to 50% strain). In the present invention, the effects of the molecular reorientation mechanism are small.

In one preferred embodiment of the present invention, the polymeric photomechanical material 30 comprises a photosensitive polyvinylidene fluoride 34 (PVDF). In that embodiment, all of the above-identified mechanisms combine to produce a photomechanical effect when the PVDF 34 is illuminated with light. However, in PVDF 34 the photothermal mechanism is the dominate mechanism. Other polymeric photomechanical materials 30 may be selected such that the photomechanical effect is produced by a combination of the above-identified

mechanisms or a subset thereof. In one such embodiment shown in Figure 6, the polymeric photomechanical material 30 comprises a photosensitive mylar 36. The photosensitive mylar 36 undergoes a comparable photomechanical effect when the mylar 36 is illuminated with light. It is thought that the dominate mechanism of the photomechanical effect in polymeric photomechanical materials 30 would remain the photothermal mechanism, although the relative contributions amongst the various mechanisms may differ.

In the preferred embodiment of the present invention shown in Figure 6, the structure of the photomechanical body 20 comprises a film or thin sheet 65 of polymeric photomechanical materials 30. In alternative embodiments of the present invention, the structure of the photomechanical body 20 comprises a fiber, strand, rod or other elongated structure of polymeric photomechanical materials 30.

In the photomechanical body 20 shown in Figure 1, the polymeric photomechanical material 30 comprises a non-isotropic polymeric photomechanical material 32 that has at least one non-isotropic, intrinsic photosensitive characteristic in that the polymeric material has at least one intrinsic photosensitive property having a parametric value that varies as regards at least one dimension of the structure of the photomechanical body 20. By proper selection of the specific polymeric photomechanical material 30 and treatment thereof, the photomechanical effect caused by illuminating such a photomechanical body 20 can provide mechanically advantageous results. In the embodiment of the present

invention shown in Figure 1, the photomechanical body 20 comprises a plate 60 of polymeric photomechanical material 30 that has been selected and treated such that there is a gradient across the thickness of the plate 60 as regards the thermal coefficient of linear expansion of the polymeric photomechanical material 30. In this embodiment, the plate 60 comprises a first major opposing surface 62 and a second major opposing surface 69. The plate 60 further comprises a first plate layer of polymeric photomechanical material 63 and a second plate layer of polymeric photomechanical material 64. The gradient of the value of the thermal coefficients of linear expansion between the major opposing surfaces 62, 69 may be linear or non-linear, depending on the specific photomechanical polymeric material and the treatment thereof. In other embodiments of the present invention, the gradient of the parametric value varies in multiple dimensions. In yet other embodiments of the present invention, the intrinsic photosensitive property of the polymeric photomechanical material 30 having a non-isotropic parametric value that varies as a gradient within the photomechanical body 20 is a non-thermal intrinsic photosensitive property, such as photoconductance. In still other embodiments, individual gradients of parametric values of multiple intrinsic properties combine to form a complex gradient of combined parametric values.

Figure 1 further shows a first plate layer of polymeric photomechanical material 63 defined by the first major opposing surface 62 and the plane bisecting the thickness dimension of the plate 60. A second plate layer of polymeric

photomechanical material 64 is similarly defined by that plane and the second major opposing surface 69. In the embodiment of the present invention shown in Figure 1, the average thermal coefficients of linear expansion in the first plate layer of polymeric photomechanical material 63 is greater than the average thermal coefficients of linear expansion in the second plate layer of polymeric photomechanical material 64. Figure 2 shows a light source 40 irradiating a surface of the photomechanical body 20 of the embodiment of the inventions shown in Figure 1. Figure 2 shows the bulk deformation caused by a photomechanical effect. The photothermal mechanism is the dominant mechanism causing the photomechanical effect in the embodiment of the invention shown in Figure 2. The light energy is absorbed by the polymeric photomechanical material 30 and is converted to heat, causing the material's temperature to increase. The plate 60 of polymeric photomechanical material 30 is sufficiently thin that the temperature differential across the plate's thickness dimension is negligible. Linear expansion occurs along the length, width and thickness of the plate 60 and causes mechanical deformation of the photomechanical body. However, in relative terms, the length of the plate 60 is significantly larger than either the width or thickness of the plate.

Referring to Figure 2, plate 60 comprises an elongated plate 61, wherein its length is substantially greater than its width or thickness such that the photomechanical deformations are most pronounced along the longest axis of the strip. The first plate layer of polymeric photomechanical material 63 will expand

more than the second plate layer of polymeric photomechanical material 64, since the temperature increase is the same for both layers and the first has a greater thermal coefficient of linear expansion. Since the plate layers are affixed to each other, the unequal expansion causes the elongated plate 61 to bend as it deforms from the bulk dimensions of the normal state surface 21 to the bulk dimensions of the actuated state surface 22. Figure 2 shows a proximal end of the elongated plate 61 affixed to a base 75. In this configuration, light source 40 irradiates the illumination surface 25 causing a photomechanical effect and producing large deflections of the distal end of the elongated plate 61 in a manner similar to that of a bimetallic thermostat strips.

Herein, a photomechanical body 20 having regions or layers of polymeric photomechanical material 30 selected or treated such that the photomechanical body 20 comprises a non-isotropic polymeric photomechanical material 32 is defined as bimorphic photomechanical body 24. In the embodiment shown in Figure 2, the bimorphic photomechanical body 24 comprises a bimorphic photomechanical plate 26 comprising two layers of polymeric photomechanical material 30. In alternate embodiments of invention, the bimorphic photomechanical plate 26 comprises multiple layers of polymeric photomechanical material 30. In additional alternate embodiments of invention, the bimorphic photomechanical plate 26 comprises a single layer of non-isotropic polymeric photomechanical material 32. Similarly, in various alternate embodiments of the invention, the bimorphic photomechanical

body 24 selectively comprises a bimorphic photomechanical film, a thin bimorphic photomechanical sheet, a bimorphic photomechanical fiber, and a bimorphic photomechanical wound strand. This invention contemplates numerous other structures of bimorphic photomechanical bodies.

As stated above, a bimorphic photomechanical body 24 may be formed by either proper selection and affixing of polymeric photomechanical materials 30 to form a non-isotropic polymeric photomechanical material 32, or by treatment of a polymeric photomechanical material 30 to form a non-isotropic polymeric photomechanical material 32. For example, a bimorphic photomechanical body 24 may be formed as a result of fabrication process of a number of polymer films such as mylar and PVDF. These polymers after being processed into thin films are usually rolled and stored into rolls. This creates an effect of "memory" in the film. After being cut into plane sheets, the film still "remembers" its initial shape in a roll. This is due to the initial packing of the polymer molecules trying to adjust for the shape of the film in a roll. The outer half of the film, which is more distal to the center of the roll, will have a greater thermal coefficient of linear expansion while the inner part tends to expand less. Thus, the process of light induced heating returns the film to its cylindrical shape. Even bending the film in the opposite direction (with respect to its original curvature in a roll) and storing it bent for a year does not change the film's tendency to return to its original curvature upon the illumination.

Bimorphic photomechanical properties can be induced in polymeric photosensitive materials by a number of techniques. One method is exposure of a photosensitive polymeric film or fiber to UV radiation. In polymers which have strong absorption coefficients for UV light, such as polyimide, this can create a modification of molecules preferably on the UV exposed side. The modification will make the exposed polymer less expandable due to light-induced heating than that on the opposite side. Other methods of surface treatment of polymeric photosensitive materials that similarly modify polymer molecular structure can be suggested for making a bimorph: ion or electron beam modification, differential drying, chemical processing by a gas or liquid, etc. An alternative method of forming a bimorphic photomechanical body 24 is to coat one side of a photosensitive polymeric film with an adhesive layer that has a substantially different thermal coefficient of linear expansion or a substantially different parametric value of another intrinsic photosensitive property. Similarly, yet another method of forming a bimorphic photomechanical body 24 is to adhere one photosensitive polymeric film to another photosensitive polymeric film that has a substantially different thermal coefficient of linear expansion or a substantially different parametric value of another intrinsic photosensitive property.

The present invention is directed to providing a simple, compact, and inexpensive means of converting low power visible or mid-infrared radiation into mechanical movement and mechanical work. In one embodiment, the actuating

light is transmitted over conventional optic fibers and through a lens assembly. In this embodiment, a low power light source of less than 300mW is used to generate mechanical displacement of the order of up to 10 mm. The light source is a visible light source which uses visible and near-infrared (400 nm to 1550 nm) light which can be transmitted through optic fibers. A pulsed light generator may be utilized for conversion of continuous light into a series of light pulses that are delayed with respect to each other. Light delivery may then be performed in the present invention by use of single or multiple mode conventional optic fibers. Beam shaping optics are used to shape the light beams to illuminate the polymer body. One embodiment of the present invention uses a polymer body made of a gold-coated 50-μm-thick film of polymer PVDF which bends along the direction of the beam of visible light sent to the film. This contrasts with the prior art's use of a bimorph based on photosensitive PLZT ceramics, which gains strain due to photovoltaic effect in combination with converse piezoelectric effect. The prior art bimorph bends when its PLZT part elongates after illumination with UV light.

The body of the photo-driven actuator is made of photosensitive piezoelectric polymer such as polyvyniledene fluoride known as PVDF. PVDF is a well known piezoelectric polymer but its behavior as a photosensitive material may be utilized for changing its shape in response to visible light.

Referring now to Figure 3, photomechanical apparatus 10 of this invention comprises a photomechanical actuator 70. The photomechanical actuator 70 shown

in Figure 3 comprises a bimorphic photomechanical body 20 having an illumination surface 25. An actuator output element 71 is shown affixed to the bimorphic photomechanical body 20. In this embodiment the actuator output element 71 comprises an actuator output arm 72, although other structures could be substituted as an actuator output element 71. The bimorphic photomechanical body 20 is shown in both its normal state, shown as normal state surface 21, and its actuated state, shown as actuated state surface 22. A light source 40 generates a light output 50, which is used to illuminate illumination surface 25. The bimorphic photomechanical body 20 deforms from the its normal state surface 21 to its actuated state surface 22 in response to illumination of the illumination surface. Such deformation moves the actuator output element 71 along path 95 to the actuator receiving element 73. The actuator receiving element 73 is adapted to receive the actuator output element 71 and be movably displaced by the actuator output element 71 along path 96, thus converting the kinetic energy of the bimorphic photomechanical body 20 into another form of energy. In this embodiment, the other form of energy is the kinetic energy of rotation of the actuator receiving element 73.

In this embodiment of the present invention, the light source 40 comprises a light generation device 41 and a light transfer device 44. The light generation device 41 is adapted to generate a pulsed light output 53. In this embodiment, light generation device 41 comprises a laser 42 for generating a light output 50 in the

spectrum between 300 nm and 10000 nm. In another embodiment, light generation device 41 comprises a laser 42 for generating a light output 50 in the spectrum between 400 nm and 3000 nm. Referring again to the embodiment in Figure 3, the light generation device 41 further comprises a pulsed light generator 48 for converting the light output 50 to a pulsed light output 53. In this embodiment, the laser 42 is an Ar-ion laser 43 operating at 488 nm. However, many other types of lasers are suitable for use in this invention, depending on the particular polymeric photomechanical material 30 selected for use in the bimorphic photomechanical body 24. Examples of lasers used in typical variations of this and similar embodiments for generating a light output 50 in the spectrum between 300 nm and 10000 nm include: He-Ne lasers; Nd: YAG lasers; Ti: sapphire lasers; tunable solid state and dye lasers; semiconductor lasers; and carbon dioxide lasers. The He-Ne laser operates at 632.8 nm. The Nd: YAG laser operates at 1064 nm and at the second harmonic of 532 nm. The Ti: sapphire lasers are tunable between 750 nm and 950 nm, while solid state and dye lasers are tunable between 400 nm and 3000 nm. Semiconductor lasers are selectable for operation at specific wavelengths from 400 nm to 3000 nm. However, the most suitable semiconductor lasers for commercial fiber optic systems are those which operate at 800 nm, 1300 nm, or 1550 nm. Semiconductor lasers; operating at 1300 nm or 1550 nm are particularly adaptable for use in long distance fiber optic communication. Carbon dioxide (CO_2) laser operating at approximately 10000 nm produces radiation that is strongly

absorbed by pure polymer PVDF. However, only limited types of optical fibers are designed to transmit Carbon dioxide (CO_2) laser radiation, and then only for relatively short distances of less than 10 ft.

Referring again to Figure 3, the light transfer device 44 of the embodiment shown comprises a fiber optic cable 45 designed to direct the pulsed light output 53 from the light generation device 41 to the illumination surface 25 of the bimorphic photomechanical body 20. In this embodiment, the light output 50 can be in the visible or infrared spectrum between 400 and 1550 nm. Operating in the visible or infrared spectrum between 400 and 1550 nm makes it practical to deliver the pulsed light output 53 to the photomechanical body 20 via conventional optical fibers without the significant loss of light energy of the prior art. In the preferred embodiment of the present invention, the pulsed light output 53 is transferred via a multi-mode fiber optic cable 45 to an optical system 47 designed to direct the pulsed light output 53 upon the illumination surface 25 of the bimorphic photomechanical body 20.

Since the bimorphic photomechanical body 20 is comprised of a polymeric material, it has significant advantages over the PLZT ceramics of the prior art. Among the advantages of polymeric photomechanical materials 30 is greater mechanical flexibility and significantly greater maximum strain in elastic deformation. Furthermore, the efficiency of conversion of the energy of light into mechanical work is higher than that of the materials of the prior art. In the

embodiment shown in Figure 3, the preferred bimorphic photomechanical body 20 comprises a photosensitive polyvinylidene fluoride (PVDF) 34. One preferred photosensitive polyvinylidene fluoride (PVDF) 34 is made from a gold coated 50-µm-thick PVDF layer forming a bimorphic polyvinylidene fluoride film 38, which is specifically adapted for reciprocally and reversibly changing its shape after being illuminated with one or multiple light beams. This provides a spring like effect. The light exposure bends the film in a first direction and then after exposure is removed, the film returns to its original position, providing a quick reciprocal movement. In one embodiment, upon the illumination with a 15-mW He-Ne laser, a PVDF film with dimensions of 5x40 mm produced a maximum static force of approximately 1.0×10^{-4} N. The force is enough to accelerate a 1-g object from rest to a speed of 10 cm/s in one second. The maximum travel distance of the free end of the bimorphic film was 5 mm over a period of time of 1 s. The bending is shown in Figure 3 with the movement illustrated by path 95.

The functional operation of the reciprocating photomechanical actuator 70 may be further understood with reference to Figure 3 where the continuous light output 50 from the light source 40 is converted by the pulsed light generator 48 to a pulsed light output 53 having certain characteristics with respect to the pulse, including pulse amplitude, pulse duration and pulse repetition rate. The pulsed light output 53 is coupled with fiber optic cable 45 and transmitted towards the bimorphic photomechanical body 24. The pulsed light output 53 is decoupled from the fiber

optic cable 45, shaped by an optical system 47. The optical system 47 directs the beam to the illumination surface 25 on the bimorphic photomechanical body 24. The bimorphic photomechanical body 24 bends and changes its shape in response to the illumination of each pulse of the pulsed light output 53. This deformation moves the actuator output element 71 along path 95 to the actuator receiving element 73 producing mechanical motion of the actuator receiving element 73 along path 96. The bimorphic photomechanical body 24 will return to its original shape after each light pulse has been removed and reset for the next pulse.

Referring now to Figure 4, an embodiment of a reciprocating photomechanical actuator 70 is shown having a two range bimorphic photomechanical assembly 12. The two range photomechanical actuator 70 includes a laser 42 for providing a coherent beam 52. A preferred embodiment uses an Ar-ion laser 43 operating at 488 nm. The Ar-ion laser 43 generates a coherent beam 52 with sufficient strength to be split into a first light output 54 and a second light output 55 by the multi-mode optic fiber splitter 46 in to the arms of the splitter 46. Each arm then goes into separate optic systems 47 through the separate pulsed light generators 48 and into separate fiber optic cables 45. The first light output 54 is directed toward the illumination surface 25.

Complex actuating motions are possible using bimorphic photomechanical bodies in various configurations. For example, two ranges of motion for a bimorphic photomechanical assembly 12 are shown in Figure 4, with both ranges of motion

moving the actuator output element 70. This bimorphic photomechanical assembly 12 comprises two bimorphic photomechanical plates 26 affixed to each other in an orthogonal orientation and each having freedom of movement in the y-z plane. This produces a trajectory of motion of the actuator output element 71 in the y-z plane. Note, that in this embodiment, the first light output 54 and the second light output 55 have the same pulse duration and pulse repetition rate. Where the light outputs 54, 55 have a generally sinusoidal pattern and the time delay between the sinusoidal patterns is close to the quarter of period, the trajectory of motion of the actuator output element 71 will follow a generally elliptical path 97. The shape of the trajectory may be varied by changing the pulse duration, pulse amplitude, and the time delay between the pulses in each light output.

Referring now to Figure 5, an embodiment of a reciprocating photomechanical actuator 70 is shown having a three range of motion bimorphic photomechanical assembly 12. This bimorphic photomechanical assembly 12 comprises three bimorphic photomechanical plates 26 affixed to each other in an orthogonal orientation and each having freedom of movement in a plane. In alternate embodiments, a single bimorphic photomechanical plate 26 is constructed in a twisted manner to provide for the three ranges of control. Figure 5 shows a first, second and third light output 54, 55, 56, each light output directed toward an illumination surface 25 of a different bimorphic photomechanical body 24 of the bimorphic photomechanical assembly 12. This produces a trajectory of motion of the actuator

output element 71 in the x-y-z space. Note, that in this embodiment, first, second and third light outputs 54, 55, 56, may have different pulse amplitude, pulse duration, pulse repetition rate, and time delay. This can produce a complex trajectory of motion of the actuator output element 71, shown as three dimensional compound path 98. The shape of the trajectory may be varied by changing the pulse duration, pulse amplitude, and time delay for at least one of the first, second or third light outputs 54, 55, 56.

Referring now to Figure 6, the drawings shows a three dimensional range photokinetic apparatus 11 for positioning an executing element, said apparatus 11 having actuator output arm 72 adapted to transfer the movement of the output point to the executing element. The actuator output arm 72 is affixed to a bimorphic photomechanical body 24. The bimorphic photomechanical body 24 comprises a thin sheet 65 of a photosensitive mylar 36 and has multiple illumination surfaces 25. In an alternate embodiment, the bimorphic photomechanical body 24 comprises a bimorphic polyvinylidene fluoride film 38. Figure 6 shows a first and second light output 54, 55, each light output directed toward different illumination surface 25 of the bimorphic photomechanical body 24. This produces a trajectory of motion of the actuator output element 71 in the x-y-z space. Note, that in this embodiment, the first and second light output 54, 55, may have different pulse amplitude, pulse duration, pulse repetition rate, and time delay between pulses in each output. This can produce rather a complex trajectory of

motion of the actuator output element 71, shown as three dimensional compound path 98. The shape of the trajectory may be varied by changing the pulse duration, pulse amplitude, and time delay of pulses for at least one of first or second light output 54, 55. One of the possible applications of this embodiment could be in non-piezoelectric drives for cantilevers of a scanning probe microscope (SPM).

Referring to Figures 11a and 11b, a photonic switch 100 is shown as one embodiment of the present invention. The photomechanical photonic switch 100 includes a bimorphic photomechanical body 24 having an illumination surface 25. The bimorphic photomechanical body 24 is formed from a photomechanical polymeric material 30 and affixed to a base 75. A light source 40 is adapted to selectively generate a light output 50 to illuminate the illumination surface 25. The photonic switch 101 is disposed in a fiber optic circuit 102 and includes a fiber optic transmitter 103, a reflector 104 affixed to said bimorphic photomechanical body 24, and at least one fiber optic receiver 105. The fiber optic transmitter 103 is adapted to generate a signal light beam 106. When the photonic switch 100 is in the closed configuration, the reflector 104 is positioned to reflect the signal light beam 106 from the fiber optic transmitter 103 to the fiber optic receiver 105 and provides optical communication across the photonic switch 100. When the photonic switch 100 is configured in the open configuration, the reflector 104 is not positioned to reflect the signal light beam 106 from the fiber optic transmitter 103 to the fiber

optic receiver 105 and, thus, interrupts optical communication across the photonic switch 100.

Referring to Figure 11a, the photomechanical body 24 of the photonic switch 100 is illuminated and undergoes bimorphic deformation sufficient to position the reflector 104 so as to reflect the signal light beam 106 from the fiber optic transmitter 103 to the fiber optic receiver 105 and provides optical communication across the photonic switch 100. Thus, in this embodiment, the photonic switch 100 is configured so as to close when the photomechanical body 24 is illuminated. Referring now to Figure 11b, the photomechanical body 24 of the photonic switch 100 is not illuminated and is in a normal, non-deformed state. In a normal state, the photomechanical body 24 positions the reflector 104 so as to not reflect the signal light beam 106 from the fiber optic transmitter 103 to the fiber optic receiver 105 and interrupts optical communication across the photonic switch 100. Thus, in this embodiment, the photonic switch 100 is configured so as to open when the photomechanical body 24 is not illuminated.

Referring to Figures 11c and 11d, a photonic switch 100 similar to the embodiment of Figures 11a and 11b is shown. Referring now to Figure 11c, the photomechanical body 24 of the photonic switch 100 is not illuminated and is in a normal, non-deformed state. In a normal state, the photomechanical body 24 positions the reflector 104 so as to reflect the signal light beam 106 from the fiber optic transmitter 103 to the fiber optic receiver 105 and provides optical

communication across the photonic switch 100. Thus, in this embodiment, the photonic switch 100 is configured so as to close when the photomechanical body 24 is not illuminated. Referring to Figure 11d, the photomechanical body 24 of the photonic switch 100 is illuminated and undergoes bimorphic deformation sufficient to position the reflector 104 so as to not reflect the signal light beam 106 from the fiber optic transmitter 103 to the fiber optic receiver 105 and interrupts optical communication across the photonic switch 100. Thus, in this embodiment, the photonic switch 100 is configured so as to open when the photomechanical body 24 is illuminated.

In preferred embodiments of Figures 11a - 11d, the photomechanical polymeric material 30 is non-isotropic. Further, the light source 40 comprises a fiber optic illuminator similar to transmitter 103 and powered by laser 42, and more particularly by an infrared laser 43 of a communication wavelength 1300 or 1550 nm. One skilled in the art will recognize that may other configurations of the photonic switch readily present themselves. For example, in one embodiment of the present invention, the fiber optic transmitter 103 and the fiber optic receiver 105 are positioned in a linear configuration such that the fiber optic transmitter 103 directly illuminates the fiber optic receiver 105 with the signal light beam 106. The photomechanical body 24 is be positioned such that it can be alternately configured either to block the signal light beam 106 and interrupt optical communication or to allow the signal light beam 106 to pass and allow optical communication. Such

alternate configuration of the photomechanical body 24 is determined by the illumination or non-illumination of the photomechanical body 24. Other embodiments of the photonic switch 100 of the present invention incorporate multiple the fiber optic transmitters 103 and the fiber optic receivers 105.

Referring to Figures 7a and 7b, a photomechanical electronic switch 90 is shown as one embodiment of the present invention. The photomechanical electronic switch 90 includes a bimorphic photomechanical body 24 having an illumination surface 25. The bimorphic photomechanical body 24 is formed from a photomechanical polymeric material 30 and affixed to a base 75. A light source 40 generates a light output 50 to illuminate the illumination surface 25. An electronic switch 91 includes a switch contact 93 affixed to the bimorphic photomechanical body 24 and at least one circuit contact 94 disposed in an electrical circuit 92. Referring to Figure 7a, this embodiment of the photomechanical electronic switch 90 is configured to position the switch contact 93 so as to close the electronic switch 91 when the photomechanical body 24 is illuminated (shown in solid lines) and to position the switch contact 93 so as to open the electronic switch 91 when the photomechanical body 24 is not illuminated (shown in broken lines). Referring to Figure 7b, this embodiment of the photomechanical electronic switch 90 is configured to position the switch contact 93 so as to open the electronic switch 91 when the photomechanical body 24 is illuminated (shown in solid lines) and to position the switch contact 93 so as to close the electronic switch 91 when the

photomechanical body 24 is not illuminated (shown in broken lines). In a preferred embodiment, the light source 40 comprises a laser 42, and more particularly an Ar-ion laser 43.

The photomechanical actuators 70 of this invention are light driven and do not require electrical power or electrical contacts. It would be highly desirable to integrate the photomechanical actuators 70 of this invention, especially as photomechanical fluidic pumps 80, into micro-electro-mechanical or micro-electro-opto-mechanical systems (MEMS/MEOMS) such as MEMS fuel cells. Two embodiments of the photomechanical actuators 70 are disclosed as photomechanical fluidic pumps 80. Referring now to Figure 8, a photomechanical fluidic pump 80 is shown comprising a fluidic diaphragm pump 86. The fluidic diaphragm pump 86 comprises a fluidic pump chamber 82, an inlet port 83, and a fluid outlet port 84. A bimorphic photomechanical body 24 is shown comprising a fluidic actuator 87 for providing actuating motion to pump the fluid 81 from the fluidic pump chamber 83 through the fluid outlet port 84. A bimorphic photomechanical sheet 89 comprising a photomechanical polymeric material 30 is disposed adjacent to the fluidic pump chamber 82 and comprises the bimorphic photomechanical body 24. A light source 40 is shown generating a pulsed light output 53 to illuminate an illumination surface 25. The bimorphic photomechanical sheet 89 is adapted to move bimorphically in response to illumination of said illumination surface by said light output, and is shown in an activated deformation, bending away from the fluid 81 in

the fluidic pump chamber 82. This generates a lower pressure in the chamber and draws fluid 81 from the fluid inlet port into the fluidic pump chamber 83. When the illumination of the illumination surface 25 is removed, the bimorphic photomechanical sheet 89 returns to its original dimensions and exerts a compressive force against the fluid 81, thus, raising the pressure in the chamber and forcing the fluid through the fluid outlet port 84. In an alternate embodiment of the invention, the orientation of the bimorphic photomechanical sheet 89 is reversed such that the sheet bends downward into the fluid 81 when activated by the illumination of the illumination surface 25.

Referring now to Figure 9, a photomechanical fluidic pump 80 is shown comprising a fluidic resonance pump 79. The fluidic resonance pump 79 comprises a fluidic pump chamber 82, an inlet port 83, and a fluid outlet port 84. A bimorphic photomechanical body 24 is shown comprising a fluidic actuator 87 for providing actuating motion to pump the fluid 81 from the fluidic pump chamber 82 through the fluid outlet port 84. A bimorphic photomechanical cantilevered beam 88 comprising a photomechanical polymeric material 30 is disposed above a resonance chamber 85 within the fluidic pump chamber 82 and comprises the bimorphic photomechanical body 24. A light source 40 is shown generating a pulsed light output 53 to illuminate at least one illumination surface 25 along the bimorphic photomechanical cantilevered beam 88. The bimorphic photomechanical cantilevered beam 88 is adapted to move bimorphically in response to illumination

of the illumination surfaces 25 by the pulsed light output 53. As the repetition frequency of the pulsed light output 53 is tuned to the proper frequency, the bimorphic photomechanical cantilevered beam 88 reciprocally deforms in a vibration tuned to a harmonic of the resonance chamber 85. These harmonic oscillations produce pressure waves within the fluidic pump chamber 83 sufficient to draw fluid 81 from the fluid inlet port into the fluidic pump chamber 83, and then to force fluid 81 from the fluidic pump chamber 83 into the fluid outlet port 84.

In alternate embodiments of the photomechanical fluidic pumps 80 shown in Figures 8 and 9, the light source 40 comprises a laser 41, specifically an Ar-ion laser adapted to generate said pulsed light output 53. A fiber optic cable 45 is adapted to direct the light output 50 from a light generation device 41 to said illumination surface 25 of the bimorphic photomechanical body 24. An optical system 47 focuses the light output 50. In variations of these embodiments, the bimorphic photomechanical bodies 24 have a plurality of illumination surfaces 25, and the light transfer devices 44 further comprising optic fiber splitters 46 adapted to split light output 50 so as to selectively illuminate the individual illumination surfaces 25. Tunable lasers 41 can be used to vary the pulse repetition pattern, pulse duration, and pulse amplitude so as to control the deformation shape and deformation frequency of either the bimorphic photomechanical cantilevered beam 88 or the bimorphic photomechanical sheet 89, depending on the type of fluidic pump 80. Where the fluid 81 does not significantly absorb or scatter the light

output 50, a coherent beam 52 of pulsed light output 53 may be transmitted through the fluid 81 to the bimorphic photomechanical cantilevered beam 88 or the bimorphic photomechanical sheet 89. Otherwise, fiber optic cable can be laid atop the bimorphic photomechanical cantilevered beam 88 (as shown in Figure 9) or the bimorphic photomechanical sheet 89 so as to directly illuminate the desired illumination surfaces 25.

Referring to Figures 10a and 10b, an embodiment of the present invention comprising a light beam focusing apparatus 110 is shown. In these embodiments the light beam focusing apparatus 110 is a self-actuating light beam focusing apparatus 110. The apparatus is self-actuating in that the light beam being focused or defocused by the apparatus causes the apparatus to deform and change the focal qualities of the apparatus. The light beam has a divergence parameter which is a measure of the change in the cross-sectional area of the light beam as it travels along a beam path. Where the light beam's cross-sectional area is reduced as it travels along its beam path, the divergence parameter is negative and the beam is said to be focused toward a focal point. Where the light beam's cross-sectional area is increased as it travels along its beam path, the divergence parameter is positive and the beam is said to be defocused from an apparent focal point.

The self-actuating light beam focusing apparatus 110 includes a bimorphic photomechanical body 24 having an illumination surface 25. The bimorphic photomechanical body 24 is formed from a photomechanical polymeric material 30.

The light output 50 is shaped by the optic system 47. The illumination surface 25 in this embodiment is flat (planar) while in the normal state and has a mirrored surface that reflects a large portion of any illuminating light. A light source 40 generates a light output 50 to illuminate the illumination surface 25 and causes the photomechanical body 24 to bimorphically deform itself into a mirrored lens.

Referring to Figure 10a, this embodiment of the self-actuating light beam focusing apparatus 110 is adapted to focus the light beam output 50 when the photomechanical body 24 is illuminated. The illumination surface 25 bimorphically deforms to form a concave, reflective surface relative to the illuminating light beam output 50. The resulting concave mirror tends to shift the divergence parameter of the illuminating light beam output 50 in a negative direction by an amount corresponding to the shape of the mirror. In the embodiment as shown in Figure 10a, the cross-sectional area of the reflected light beam (shown in broken lines) is reduced as the reflected light beam is focused toward a focal point. Referring to Figure 10b, this embodiment of the self-acting light beam focusing/defocusing apparatus 110 is configured to defocus (or difuse) the light beam output 50 when the photomechanical body 24 is illuminated. The illumination surface 25 bimorphically deforms to form a convex reflective surface relative to the illuminating light beam output 50. The resulting convex mirror tends to shift the divergence parameter of the illuminating light beam output 50 in a positive direction by an amount corresponding to the shape of the mirror. In the embodiment as shown in Figure

10b, the cross-sectional area of the reflected light beam (shown in broken lines) is increased as the beam diverges away from an apparent focal point. In a preferred embodiment, the light source 40 comprises a laser 42, and more particularly an Ar-ion laser 43. The applications of this embodiment of the invention include long distance open air light transmission lines (focusing) and protection of sensitive photodetectors against intensive laser radiation (defocusing).

Other similar embodiments of the light beam focusing apparatus 110 of this invention include embodiments where the photomechanical body 24 and its illumination surface 25 is either convex or concave in the normal, non-illuminated state. Still other embodiments are not self-actuating and include two or more light beams. In these embodiments, a light beam output 50 used to activate and shape the bimorphic deformation of the illumination surface 25. The deformed illumination surface 25 is then used to focus or defocus a second light beam. The second light beam would be of a frequency not causing a photomechanical effect in the photomechanical material selected to comprise the illumination surface 25. The photomechanical body of yet additional embodiments would transmit rather than reflect a large portion of the light beam output 50. In such embodiments, the convex illumination surfaces 25 would tend to focus the light beam output 50 while the concave illumination surfaces 25 would tend to defocus the light beam output 50.

Further advantages of the present invention include:

(a) The photomechanical actuator 70 generates greater mechanical displacement with greater energy conversion efficiency than the prior art actuators;

(b) Activating light in the visible and infrared spectrum can be delivered to the bimorphic photomechanical body 24 through conventional communication optic fibers without significant power losses;

(c) The polymeric photomechanical material 30 can be easily processed and shaped using a variety of techniques such as molding, stamping, bending, and cutting;

(d) The polymeric photomechanical material 30 is suitable for thin film technologies such as spin casting, spraying, dipping, vapor deposition, contact printing, and photolithography, thus making it possible to integrate the photomechanical actuator 70 into micro-electro-mechanical or micro-electro-opto-mechanical systems (MEMS/MEOMS);

(e) The photomechanical fluidic pumps 80 of this invention are light driven and do not require electrical power or electrical contacts, thus making it advantageous to integrate the photomechanical fluidic pumps 80 into micro-electro-mechanical or micro-electro-opto-mechanical systems (MEMS/MEOMS) such as MEMS fuel cells;

(f) A variety of trajectories of mechanical motion of the photomechanical actuator 70 can be achieved without changing an embodiment by simply changing the characteristics of the pulsed light output 53, such as pulse intensity, duration, repetition pattern, time delay between pulses, or by refocusing the pulsed light output 53 on different illumination surfaces 25 of the bimorphic photomechanical body 24;

(g) Photomechanical bodies are comprised of impact and stress resistant polymeric photomechanical materials 30; and

(h) The photonic switch 100 of this invention is driven by the same optical signal as those being switched and does not require conversion into electric signal at any stage, thus making it advantageous to integrate the photonic switch 100 into photonic communication circuits with the highest up-today data flow rates.

Uses of the present invention include: light-driven micro-electro-mechanical systems (MEMS) and micro-electro-opto-mechanical systems (MEOMS); smart materials or skins; and photonic switches based on photo-driven deflectors.

Thus, although there have been described particular embodiments of the present invention of a new and useful "Bimorphic Polymeric Photomechanical Actuator," it is not intended that such references be construed as limitations upon the scope of this invention except as set forth in the following claims.